Energy recovery methodology in industrial processes

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Abstract
Through the CERES -2 project, supported by the French Research National Agency (ANR), we have developed an open source software platform, called CERES, to optimize heat recovery in continuous industrial processes.
This platform is based on a multi-scale and multi critera methodology for heat recovery optimisation. This methodology is based on the following calculation steps:

1. Minimum Energy Requirement identification
2. Minimum Exergy Requirement and utilities identification
3. Exchanger network construction

At each step we solve a linear mono-objective problem. The first step allows, from a set of heat flows, to build the composite curves and to determine the minimum heating and cooling energy requirements. With the set of heat flows and a solution of the first step, the second step proposes the introduction of utilities, such as heat pumps or organic Rankine cycle (ORC), to minimize the exergy destruction. The last step is based on an algorithm of heat exchanger network design (HEN) including utilities and heat recovery technologies sizing, based on economic criteria.
The set of heat flows are constructed in the platform CERES from industrial processes Modelica models.
CERES has been validated with 3 industrial case studies.

Key words:
Pinch method, exergy, HEN, multi-criteria optimization

Introduction
Annual energy consumption in industry in France is about 456 TWh, 70% of which is dedicated to heat needs. Although the energy efficiency of French industry is one of the highest in the world, there are still very significant potential energy savings, particularly through heat recovery [1]. Several studies [2] have shown that theoretically 10 to 25% of the energy from boiler, furnace and dryer exhaust gases can be recovered, which represents between 35 and 85 TWh/year for France [3]. Europe (through standards and directives) and France (through systems such as energy saving certificates (CEE) or CO_2, emission quotas) impose constraints on manufacturers to encourage these savings.
Manufacturers need to optimise their energy consumption. Difficulties to achieve this is due to the diversity of fatal heat sources (nature, temperature, etc.), the diversity of available production and recovery technologies and the different criteria to be taken into account for optimisation: economic, energy and environmental.
The purpose of the CERES-2 project was to develop an optimisation platform to support manufacturers in their investment choices, by identifying optimum solutions for the reuse of fatal heat. The developed resolution method in the CERES platform [4] combines mathematical solvers, optimisation algorithms and the pinch method. This method developed by Linnhoff [5] is used for the energy and economic study of an entire process through the description and analysis of heat fluxes. Complementary work has established general rules for the selection of utilities suitable for a process [5]. However the pinch method has some limitations. Theoretically, it cannot take account of industrial constraints such as geographic distance which will prevent heat exchange between two fluxes: In this case the results obtained are not relevant. In practice, it is sometimes too complex to use because the analysis of curves by a non-expert is difficult and calculation times become long as soon as there is a significant number of fluxes being studied.
Therefore, this method has been extended in order to mitigate these limits. At the present time, each optimisation problem (energetic, exergetic, and/or economic) may be solved simply using a special algorithm making use of solvers or single or multi-objective optimisation algorithms.
This paper presents firstly methodological developments made on the selection and optimisation of heat recovery technologies in the solution of an energy integration problem implemented into the CERES tool. Secondly, an industrial application case (oil refinery) illustrates use of the platform to design and optimise utilities.

Methodology
The methodology developed in the CERES platform shall satisfy a complex problem: to solve a problem with many parameters and design variables (discrete and/or continuous), leading to technologically viable solutions, in a time

compatible with industrial requirements.
The main steps are the following:

1. Identification and quantification of heat recovery potentials within an industrial process. The pinch method developed by Linnhoff is used.
2. Specification of efficient utilities and thermodynamic heat recovery systems (heat pumps, Organic Rankine cycles, cogeneration unit, etc.) [6][7].
3. Construction and optimisation of the heat exchanger network (HEN). Construction of the HEN can be considered to be a linear combination problem [8][9].
4. Optimisation of specified equipment.

Although the potential for recovery and construction of the heat exchangers is derived from the existing practice, the specification and optimal design of utilities are innovative because they combine the exergetic analysis with the energetic analysis of the pinch method. These are the two main steps that are developed below.

The purpose of the step 2 is to propose high performance thermodynamic utilities based on the profile of power needs as a function of the temperature (called the Large Composite Curve by Linnhoff [5]) and using a criterion that minimises the destruction of exergy. The number of utilities is then limited, while guarding against forgetting about relevant solutions. This module proposes the following systems:

- Heat pumps that exchange with an ambience (the atmosphere, subsoil or water);
- Heating and cooling pumps which combine a cooling need and a heating need between process fluxes directly;
- Organic Rankine Cycles or more generally engine cycles;
- Heating utilities (cogenerations) and cooling utilities (chilled water production).

Each of the utilities mentioned above makes exchanges at constant temperatures and is modelled in the same way as a heat pump: cooling and heating power, an exergetic yield or efficiency depending on these temperatures and two variables, one continuous and the other binary, for the design of the installed power and whether or not the utility is used. However, as seen in Fig. 1, their position depends on the pinch temperature (Tp), the ambient temperature (T0) and their corresponding position.

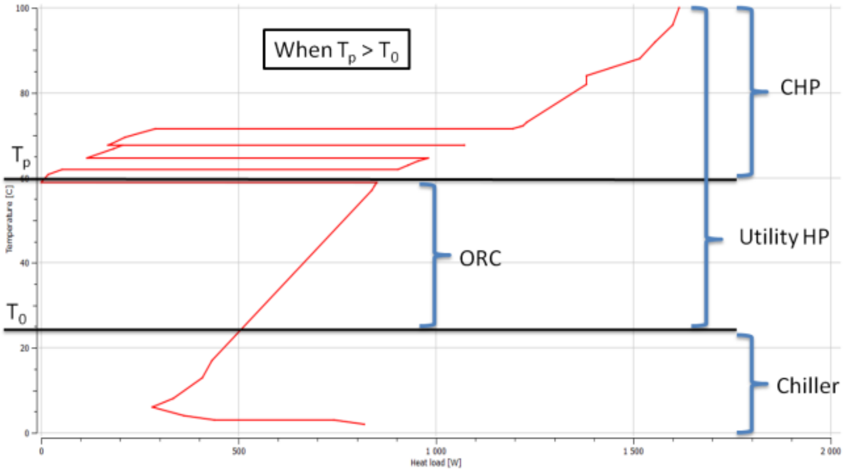

Fig. 1: Positioning of the additional utilities depending on temperatures

The developed algorithm minimises consumption/destruction of system exergy while selecting and sizing the appropriate utilities [6][7]. It thus quantifies the available exergetic flux (cooling above ambient temperature) and/or exergy needs (heating above the pinch temperature and cooling below ambient temperature). The exergetic efficiency considered a priori can approach the performances of real conversion systems (motors or receivers).

The preselection module thus specifies heat reuse or recovery equipment. This specification is thus expressed in source and well temperatures and the power of the equipment. The equipment must be designed and optimised to reach at least the physically acceptable exergetic efficiency assumed a priori, if the benefits of this solution are to be demonstrated.
The CERES platform uses Metaheuristic algorithms with the following characteristics: rules and contingencies are combined to mimic natural phenomena, derived calculations are not necessary; and the most advanced methods are evolutionary and genetic algorithms.
In this work, the multi-criteria optimisation done for the simple Organic Rankine Cycle (ORC) with four principal components: pump, evaporator, turbine and condenser maximises the efficiency in the sense of the first principle (1), the exergetic efficiency (2) and the power (3), with the design variable being the reduced pressure (i.e. the ratio of the

evaporation pressure to the critical pressure of the cycled fluid) that can vary from 0.4 to 0.7. Equations of the objective functions are also:

$$\eta_I = \frac{W_{ORC}}{Q_h} \tag{1}$$

$$\eta_{Ex} = \frac{Ex_{useful}}{Ex_{used}} = \frac{W_{ORC}}{Ex_h} \tag{2}$$

$$\dot{W}_{ORC} = \dot{W}_t - \dot{W}_p \tag{3}$$

Case study

In this work, the preheating process of crude oil for the method for fractioning oil into main components such as naphtha, gasoline, kerosene, and fuel oil [3] is taken as a case study for integration of the ORC cycle.

Heat flux data with input and output temperatures and thermal loads derived from the enterprise's scheme are input into the CERES platform. A ΔTmin global temperature of 20°C is used as the energetic and economic target. Fig. 3 shows the large composite curve (GCC) plotted from these fluxes.

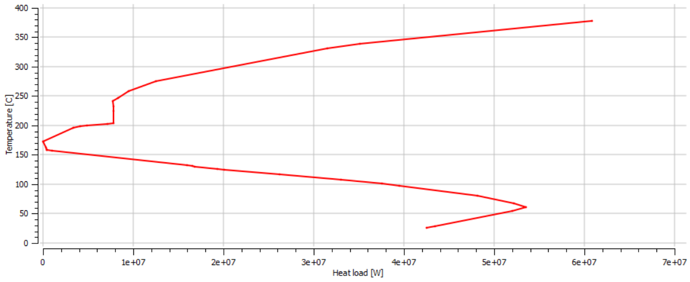

Fig. 3: GCC for the studied process

Reading this GCC shows that below the pinch temperature of the process (at 160°C), of the order of 40 MW of cooling need is available between 150°C and 100°C. There is then a self-sufficient pocket of the order of 10 MW located at between 100°C and ambient temperature (crude oil input temperature).

The use of the preselection module (a priori assuming a 50% exergetic efficiency for ORCs) suggests the use of Organic Rankine Cycles (limited to 1 and then 2 items of equipment in cascade in the simulations) to reuse the exergy contained in the fluids to be cooled Fig. 4 and Fig. 5 present the results.

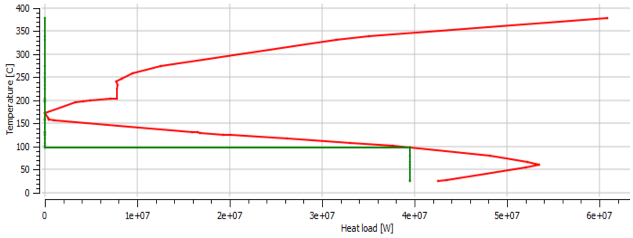

Fig. 4: Integration of one ORC

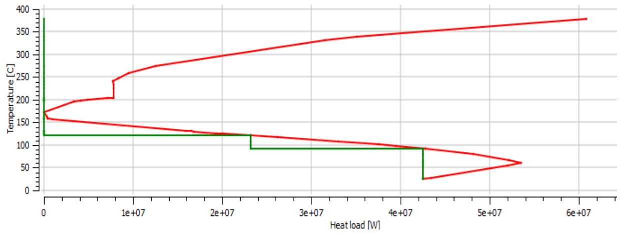

Fig. 5: Integration of 2 ORCs in cascade

When the number of ORCs is limited to 1, the preselection module proposes an ORC taking 39 MW of heat with a source temperature at 100°C. This ORC has a production potential of 3.7 MW of electricity. Integration of 2 ORCs in cascade makes it possible to draw off the entire cooling need (42 MW). Drawing off is done at two source temperatures (120°C and 90°C). They have a combined production potential of 43 MW of electricity.

A priori, the small difference of exergy evaluated for the two cases (1 ORC and 2 ORCs) suggests that it would be difficult to economically justify the investment in two items of equipment.

The results of the multi-criteria optimisation by CERES are presented in the form of Pareto charts with two objective functions (see Fig. 6): η_I (efficiency in the sense of the first principle) *vs.* η_{Ex} (exergetic efficiency). Each point on the Pareto chart is a potential optimum. Therefore, selection of the work point depends on the operator's experience or the priority order of objectives. In this study, an ideal point is a hypothetical point on which two objective functions reach their optimum values (Fig. 6). This point is not located on the Pareto chart. The optimum point on the Pareto chart is determined as the point closest to this ideal point.

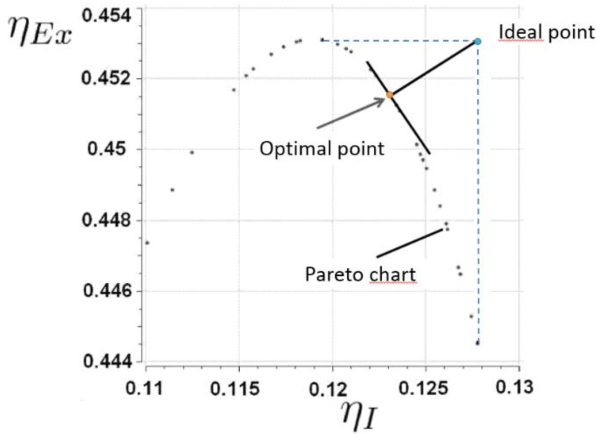

Fig. 6: Pareto chart between η_{Ex} and η_I

The optimisation results presented in Fig. 6 show that the designed ORC has an exergetic efficiency of more than 45% which corresponds to the assumption of a 50% exergetic efficiency assumed in the preselection module. However the calculated electrical power is 20% higher than the power estimated by the preselection module. This difference is related to the variation of the organic fluid in the boiler (preheating and evaporation) so that it is possible to operate at an average entropic temperature (equivalent source temperature) higher than the hot source outlet temperature. Therefore the design and optimisation of the ORC model can validate the energetic and technological relevance of an optimised ORC solution in this crude oil preheating process. Therefore the subsequent step to design the heat exchanger network and to select utilities based on economic criteria provides a means of evaluating the cost effectiveness of such a solution.

Conclusion

In conclusion, this paper demonstrated the methodological developments made with the CERES methodology for the selection, design and optimisation of utilities through an industrial case. They provide a method of proposing the best energy recovery paths through an energetic and exergetic analysis of industrial process flows. These developments integrated into a broader methodology for selecting utilities and creating the heat exchanger network based on economic criteria, enable a complete analysis of an energy integration problem. The method proposes a multi-scale approach: varying from a fast analysis of the potential and a specification of equipment operating conditions to the optimised detailed design of the proposed technologies. The progressiveness of the methodology means that the analysis can be refined as a function of the potentially achievable energy efficiency and the precision of input data.

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